NIPER-342
Distribution Category UC-122
March 1988

STATUS REPORT

STATIC PORE STRUCTURE ANALYSIS OF RESERVOIR ROCKS

Project BE12A, Milestone 2, FY88

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Work Performed for the
U.S. Department of Energy
Under Cooperative Agreement
DE-FC22-83FE60149

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STATIC PORE STRUCTURE ANALYSIS OF RESERVOIR ROCKS

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ABSTRACT

The objective of this work is to study pore structures and develop methods for computerized, petrographic image analysis to quantify the effect of petrophysical properties in reservoir rocks. The entrapment of oil and gas in a reservoir is dependent to a large extent on the pore geometry of rocks. Petrographic image analysis (PIA) offers a relatively new technique for measurement of the pore complex of rocks. The technique provides a method for capturing detailed information in digital form of the shape, surface area, and size distributions of rock pores. Through proper statistical analysis and data correlations, pore image parameters can potentially provide estimates of porosity, permeability, and radius of the pore throats. The technique can also provide information for the analysis of grain size or grain shape. This information will be useful for characterizing the net effect of depositional environments and diagenesis on pore structure. This report describes work performed from October 1987 through April 1988 to obtain equipment, software, and the application of image analysis to measurements of rock properties. This report represents the completion of milestone 2 of the FY88 work plan.

INTRODUCTION

Image analysis is a relatively new tool to be applied to petrographic studies. In order to obtain detailed pore structure informantion of reservoir rocks by petrographic image analysis (PIA), a magnified image must be acquired, digitized, stored, and then computer processed. Computer-assisted analysis of pore properties requires an acquisition system consisting of (1) a microscope image, (2) a video-scanner, (3) a digital converter, and (4) a computer with a frame grabber for data storage and processing.

One of the initial tasks of this project was to evaluate and procure equipment and software for in this project. Our initial evaluation of PIA was carried out on an existing image analysis system. It was useful only for obtaining preliminary pore imaging data, testing of components, and demonstrating some of the inadequacies of the present system and desirable features for future equipment procurements.

Previous Work With PIA

An extensive review of the literature was made for petrographic image analysis (PIA). A thorough knowledge and understanding of prior work is an important part of the future direction of this project. The work of the two primary ~~two~~ investigators in this field (Ehrlich[1] and Ruzyla[2-3]) will be discussed below.

Robert Ehrlich and his coworkers at the University of South Carolina have spent the past decade working on the applications of image analysis for measuring rock properties. Their work has been limited to microscopic images of thin sections. Much of Ehrlich's work has been performed in the development of statistical methodology and software for measuring petrographic images. To obtain statistical accuracy, the correlation of petrographic features with image data requires the analysis of many images. Each image contains a large data set of pore size, shape, and distribution frequency. Ehrlich has aggressively developed statistical analysis methods to transform image data into petrophysical data.

Ehrlich and other investigators have used errosion-dilation procedures for computer analysis of image size and shape. The number of erosions necessary for pore disappearance is one method of measuring feature size.

In addition, the erosion-dilation (E-D) process removes small scale irregularities from the surface of the feature and provides a way for measuring surface roughness. The E-D cycle is a process where one or more layers of pixels are stripped from a features's image surface (much like peeling an orange) and then one or more slightly modified layers are added to the feature image surface.

Measurement of pore connectivity from 2-D images is an important parameter for relating fluid flow through rocks. Computer-driven image erosion analysis provides a method of measuring pore connectivity and pore throat size.

The correlation between fluid flow and PIA data has been a primary goal of Ehrlich and his coworkers. Their procedure consists of correlating the porosity types obtained from PIA with fluid flow data obtained by mercury injection or permeameters. Also, a calibration step is crucial for predicting fluid flow by PIA of similar rock types or representative rock suites.

Thereafter, the porosity classifications for PIA are used to predict fluid flow response for of a specific stratagraphic sequence or rock type.

Ehrlich has developed the following criteria for describing fluid flow by PIA analysis. Pore size distributions are determined for pores according to five or six size intervals ranging from less than 2.5 up to 200 μm. The size distributions are further categorized according to the number of smooth and "rough" pores. The pore data are also classified according to pore size and the number of connected pores or "coordination levels". By correlating these pore classifications with laboratory flow fluid data, Ehrlich suggests that fluid flow properties can then be predicted from PIA of samples of the same rock type.

Whereas the previous work used a statistical analysis for the application of PIA data, K. Ruzyla[1] has used a more direct analytical and theoretical approach to the application of image analysis. He emphasizes the measurement of pore size distribution, pore surface area, pore shape, and porosity by image analysis. He also stressed the errors associated with using transmitted light images of thin sections. Therefore, for much of his work, images obtained from back-scattered SEM and incident fluorescent light are used. He indicates that these techniques provide better contrast and image detection between the pore and matrix rock material.

EXPERIMENTAL

At the start of FY88, a relatively low cost imaging system was available at NIPER. It was realized this system was not adequate to meet the objectives of this project. Therefore, the initial efforts of this project focused on surveying commercially available imaging systems for their capability and application for petrographic image analysis.

Task 1. Evaluate NIPER's Image Analysis System for Characterizing Rock Pore Structures.

The primary objective of this task was to gain familiarity with image analysis equipment, define the system deficiencies, and provide insight for equipment procurement. The task objective was not intended to change, modify, or improve the imaging system.

This system consists of the following components:

(1) Nikon petrographic microscope,

(2) Magnavox video camera and VCR,

(3) Image capture board with three-color capability, and

(4) Imaging software - Imagit™ and Imagepro™ by Chorus Data Systems.

The microscope is a high quality instrument which should be adequate for the purposes of this project. A UV lamp attachment was procured for the microscope as an excitation source for fluorescent samples. The fluorescence technique offers the potential of greater contrast for pore-rock matrix interfaces. The primary difficulty in using fluorescence is the low light intensities obtained from fluorescent materials.

The Magnavox video camera presently in use at NIPER is a 240-line, color camera. A higher resolution camera would be desirable to increase the detail of the captured images; however, higher resolution color cameras were available only at a high cost. Within the past 2 months, several companies have announced a new series of color, 480-line cameras (super VHS) which cost in the range of $1,500 to $2,000. We plan to ~~obtain~~ have a demonstration of these new cameras to compare improvement of picture quality and consider the possibility for future procurement.

The Image capture board was procured from Chorus Data Systems. This board has a three color-512x480x6 bit capability. The resolution of the frame grabber is adequate for this project. However, the 6-bit or 64-color level may be somewhat inadequate for some applications where subtle intensity levels are required. This is especially true for gray level images, such as fluorescent images or black and white SEM photographs.

The primary consideration for image analysis is the capability of the imaging software. The image software of the Chorus system (Imagepro™ and Imagit™) is the main system limitation, and manual manipulation is required for feature measurements. For example, pore dimensions (axis and perimeter) measurements must be manipulated by the operator using the computer system mouse. Some image manipulation is possible, including erosion/dilation and image filtering, but each step requires operator interaction.

One important step in image analysis involves setting the threshold to define feature boundaries to be measured. With the Chorus system, the operator must manually adjust the threshold level of a captured image. For a petrographic slide, this is the boundary between the pores and rock matrix. Therefore, setting the threshold level accurately depends on the contrast of the rock/pore interface and the experience or skill of the operator. For an imaging system with more sophisticated software, it may be possible to automate the selectionof the threshold level. An attempt will be made to automate threshold level selection in image analysis methodology as a part of Task 5.

A few thin sections from the Bell Creek reservoir were analyzed by PIA for pore area. For example, pore areas of 26.6, 28.3, 29.6 and 32.3% were measured for different portions of one thin section. An average pore area value of 29.2% was considered reasonable when compared to the original rock porosity of 29.7%. However, it is evident that there is considerable porosity variation in the rocks. Since only small areas are examined for each petrographic image, multiple images must be examined and averaged to obtain a representative analysis of a rock sample. In addition, all size pores must be accounted for, thereby increasing the number of images (at different magnifications) necessary for evaluating a complex pore system with a wide size distribution. Therefore, measurement of porosity by image analysis requires the capture, and analysis of multiple images to obtain statistically accurate values.

The greatest weakness of the original image analysis system was the system software. Procurement of additional equipment must include the capability for automated feature detection and feature analysis.

Task 2. Enhancement of Image Analysis System

In exploring the various options for upgrading the image analysis system, we concluded that system cost would be the controlling factor. Imaging systems with more sophisticated software packages are available at proportionately higher costs. Several high quality systems were eliminated from consideration simply because equipment costs exceeded budget constraints. Tracor Northern Inc. and Kevex Corp. are suppliers for high-quality image processing systems. Costs of these systems varied with system options but were in excess of $50,000. Another system was offered by

Princeton Gamma Technology (PGT) at a cost of about $50,000. This system had an additional advantage of directly processing images from scanning electron microscopy (backscatter electron and electron dispersive x-ray images). The PGT system also offered a reasonably sophisticated software package for feature analysis.

We also explored procurement of software from researchers at the University of South Carolina. Perception and Decision Systems, Inc. (PADS) is the vendor for licensing this system. The advantage of this system was software designed specifically for petrographic analysis. Again the cost far exceeded the budget for equipment in BE12A. Over a month was spent trying to negotiate a lease/purchase contract. Negotiations were discontinued because of the high cost extending over 3 years. Also the software was proprietary with PADS which offered little opportunity for modification of the software for other research applications.

Finally, two other imaging systems were considered because they were available within budget requirements. A relatively low-cost monochrome system (CUE 2) by Olympus, Corp. was eliminated because the software for feature analysis was not flexible to modifications for our applications. An imaging system from American Innovision Inc. was judged to be the best system (within budget constraints) for our application. The hardware has color capability (3 - 680x480x24 bit frame grabber). The system also has options for automatic feature detection with a rather unique "J" language which allows the operator to program automatic test routines for feature analysis. This system was procured and received in early March. The system is operational, and we are presently becoming familiar with the system software and evaluating methods for application of the system software to requirements of this project.

Task 3. Methodology Investigations for Pore Structure Reproduction and Microscopic Imaging

Selection of Rock Samples for PIA Investigations

Rock samples from the Bell Creek reservoir were chosen for initial investigations in this project. Cores from Bell Creek were available with a wide variety of petrographic features including cores with high values for porosity and permeability. In addition, some petrographic information for these cores was available from the Reservoir Characterization Project BE1. Information derived from PIA may also be useful in further characterizing the Bell Creek reservoir.

Prepare Thin Sections

A number of thin sections of rock samples from the Bell Creek reservoir were available. Thin-section examination has shown that some of these thin sections contain grinding materials and gas bubbles trapped in the impregnating epoxy resin. Grinding materials embedded in thin sections reduce the contrast between rock grains and pores. Gas bubbles trapped in the resin can be erroneously identified as rock grains by image analysis.

Several sets of thin sections were ordered from another vendor to determine whether higher quality thin sections could be obtained from a different source. Both single- and double-polished thin sections were ordered to determine whether the additional cost warranted polished thin sections. With transmitted light, the "regular" thin sections are greatly inferior, and the doubly polished thin sections have a much brighter and cleaner appearance. Using UV fluorescence, however, no significant difference can be seen between single and doubly polished thin sections, and the regular thin sections remain inferior. Trapped contaminants in the regular thin sections make PIA measurements untrustworthy. We concluded that single-polished thin sections would be the all-around best, most cost effective type of sample.

Other Methods for Improving Microscopic Images

The problems associated with image acquisition from thin sections using transmitted light are a primary limitation for correctly detecting features by PIA. For thin sections, the epoxy resin impregnation can be extremely thin at the rock/pore interface. Consequently, the light intensity contrast for transmitted light is often insufficient to accurately define grain boundaries. Therefore, investigations of alternative sample preparation and image acquisition methods were made to improve contrast for accurate feature detection.

Several methods were considered for improving image contrast. These included images obtained using incident fluorescent light of resin-impregnated rocks and SEM photographs of backscattered electron images (BEI) of rock and pore casts. Each technique may offer advantages for obtaining representative and accurate image features.

Figure 1 shows an example of a pore cast taken from the Bell Creek reservoir (Well 16, depth 4,328.5 ft). The SEM-BEI photograph shows excellent detail of not only the larger pores and pore connectivity but also smaller secondary porosity resulting from silt and clay inclusions. SEM-BEI photographs also have an inherent 3-dimensional quality. Resin-impregnated samples which have been polished flat but not etched could be prepared more quickly and provide sharper grain boundaries. However, preliminary back-scattered electron images from samples prepared in this manner are disappointing with regard to contrast between pore and grain bodies. To seriously consider using the BEI technique, we would have to significantly upgrade our SEM hardware. Although there are advantages to the pore cast and polished slab method, the additional time required to prepare pore casts does not justify their use for initial image studies. Pore casts may be used in future work when image analysis techniques are developed.

A Dage MTI black/white video camera which is capable of detecting images with low light intensity was recently received. The camera will be particularly useful in capturing fluorescent images and help quantify the work to improve fluorescent images.

Fluorescent light images may be the most applicable method for the purposes of this project. Therefore, most of our effort has concentrated on investigating fluorescent techniques. The main difficulty with fluorescent light is the relatively low light intensity. This problem has been partly solved by the purchase of the new black and white video camera. Our experience has shown that the epoxy used to impregnate thin sections can vary in inherent fluorescence. Fluorescent enhancement of epoxy has not been successful with the addition of fluorescent dyes. The dye materials presently available do not mix uniformly with the resin which results in patchy fluorescence. The fluorescent dyes also tend to be water soluble which adds to the cost of preparing thin sections.

Another potential method for increasing epoxy fluorescence is the use of fluorescent stains. A number of stains were obtained and applied to existing thin sections according to procedures developed by Ruzyla and Jezek.[3] Initially, no apparent enhancement was observed in fluorescent intensity using the epoxy stains. However, with further effort, the epoxy surfaces were cleaned and treated so that stain application resulted in improved fluorescent intensity. There was little improvement, however, in fluorescent contrasts between the rock pores and grains. We will continue to search for epoxy materials and suitable dyes or stains that will increase fluorescence of epoxy impregnated rocks.

Our greatest success in enhancing the fluorescent contrast between grains and pores has recently been achieved with a fluorite objective. The advantage of a fluorite objective is a larger aperture and a higher transmission ratio of UV light. This results in approximately 40% more transmitted light to the video camera. Preliminary testing of fluorescent images obtained with the fluorite objective showed higher fluorescence intensity values and greater contrast between epoxy pores and rock components.

An example of the difference between the fluorite and glass objectives is shown in figure 2. The figure shows a histogram of pixel intensity for captured images. The fluorite image has significantly higher fluorescent intensity and better pore/grain contrast. For thin section W4-4416.7, there is no clear transition zone between rock pores and rock grains when the glass objective is used.

Finally, one other technique was investigated to enhance fluorescent images by changing the excitation filter for the UV incident light. The purpose of the excitation filter is to limit the wave length of transmitted light from the mercury light source to the petrographic slide. Sample fluorescence can be enhanced by matching the incident light wavelength necessary to achieve fluorescent excitation in the sample. Three excitation filters are presently available with our microscope. These are excitation filters with a wavelength band pass of UV (330 to 380 nm), blue (470 to 490 nm), and green (510 to 560 nm). Tests with the blue filter indicated less sample fluorescence than with the UV or green filter.

Figure 3 shows the pixel intensity histogram comparison of fluorescent images obtained using the green and UV filters. Light from the UV filter produced fluorescece in the rock grains and no visible fluorescence in the epoxy-impregnated pores. The UV filter produced a reverse polarity of the image with pores space represented as dark areas. It is possible that the reverse image may have application in future image analysis. However, as shown in figure 3, the green filter produced better contrast, especially in the mixed gray level transition zone between the dark rock grains and the lighter pore space.

Furthermore, improvements may be possible with other excitation filters. An excitation filter (400 to 440 nm) has been ordered to examine sample fluorescence using blue-violet light.

Task 4. Petrophysical Measurements of Rocks and Cores

One of the problems in obtaining petrophysical data is sample variability. Analysis of core plugs usually gives an average value. For example, core plug porosity does not provide a measure of porosity variations within the sample. Image analysis examines only small sample areas; therefore, several images must be captured, analyzed, and averaged to obtain a representative value for the rock. In addition, it is also desirable for the thin section to be cut at a location as close as possible to the petrophysical core plug.

Presently, several thin sections from other projects are available for image analysis. For some of these thin sections, analytical data (porosity and permeability) are available; however, core data and corresponding thin sections may not be from exactly the same location or close proximity. In addition, other petrophysical data, such as capillary pressure by mercury injection, are usually not available. The thin sections are presently used for the purposes of image capture and initial analysis experiments. But these thin sections may not be satisfactory for petrophysical correlations. As techniques and procedures are developed for PIA, additional thin sections closely matched to petrophysical measurements will be required for data correlations.

A survey of Teapot Dome cores was made to select suitable core intervals for image analysis and measurement of physical properties. A total of 12 relatively uniform sandstones were selected. The core samples were from seven different wells in the Naval Reserve Field No. 3, Natrona County, Wyoming. Core depths ranged from 276 to 320 ft. These cores were plugged (1-in. diameter) and cut into two 1.5 in. sections for porosity and permeability measurements. The values for porosity and permeability are listed in table 1. Most of these values were relatively consistent for adjacent plugs. End segments of the core plugs will be used to prepare thin sections. Presently, we are investigating methods to enhance epoxy fluorescence. After methods for obtaining satisfactory thin sections are developed, thin sections will be prepared.

Task 5. Application and Investigation of Imaging Analysis Methodology of Rock Pore Structures

Limitations of PIA for Small-Scale Features

Even with the greatly improved image contrast provided by the fluorite objective, severe problems still exist for samples with clay-rich or silty interstitial materials. These samples have a proportionately greater amount of small-scale pores or microporosity. Because of the small scale, the pixel resolution may not be sufficient to resolve details of the captured image. If the pores and grain sizes are approximately the same size as are the video pixels, the video image is represented by a large number of pixels which are mixtures of rock, matrix, and pore space.

An example of a thin section with abundant clay and silty materials is shown in figure 4. In this sample (P2-4437.1) the intergranular space is filled with clays and fine-grained materials. Rock porosity is represented as small-scale pores. Figure 4 is a pixel histogram versus pixel intensity of the rock sample containing microporosity. As shown in figure 4, there is virtually no contrast between the dark rock grains and lighter fluorescent pores. Most of the pixels represent an overlap of small-scale pores and rock matrix.

To some extent, the problems associated with image analysis of fine-grained rocks containing microporosity can be overcome by increasing microscopic magnification. However, there are also practical limitations to small-scale analysis. As magnification is increased, the analysis area becomes smaller, detectable light intensity is reduced, and microscopic aberrations reduce the image contrast and sharpness. In addition, the pixel resolution may not be sufficient to resolve details of the captured image. In summary, there are severe problems and limitations for the application of image analysis to fine-grained rocks containing microporosity.

American Innovision Software Capability

The software package of the American Innovision (AI) system has the following operational features:

(1) image capture and storage in data files;

(2) manual adjustment of pixel intensity threshold to differentiate image features and background to create a binary image;

(3) erosion/dilation operation of binary images;

(4) binary measurements of image features including: areas, x and y feret diameters, centroid, and number of features; and

(5) percent transmission.

One major advantage of this system is that the operational steps (except threshold adjustment) can be programmed for automatic execution using a "J" language series of commands. The results of the measurements can be stored in ASCII files, from which they can be accessed for further manipulation using plotting or statistical analysis software packages such as Lotus or Statgraphics.

The present software lacks the capability for several feature measurements and operations. One of the major inadequacies of the software is the automatic measurement of the features for determining maximum and minimum diameters. These measurements are necessary in the development of programs to measure grain/pore size distributions and fluid flow properties. We have asked AI to develop diameter measurement as part of the software package.

In addition, some additional feature analysis operations are not available with the present software package, such as statistical analysis and histogram representation of the feature size/shape distribution. More sophisticated image analysis systems often contain more comprehensive software packages. However, these systems are available at a proportionately higher cost. We will continue to change or modify the software as we gain familiarity with the system and the requirements necessary for this project.

SUMMARY

Progress on this project has closely paralleled the tasks outlined in the FY88 work plans. Equipment procurements were made for capturing petrographic images and data analysis. The software appears to be reasonably versatile with the capability for programmed execution of measurements and data analysis. The curent software lacks the capability for several feature measurements. We have requested that AI develop these measurements as part of the software package. The development and application of software to feature detection and data analysis will be a major part of this project in the coming months.

Microscopic images with a sharp contrast between the pores and rock matrix is critical for accurate detection of rock features. To date good progress has been made in improving contrast of captured images. Our efforts will continue to improve the detail and contrast of microscopic images.

Taking into consideration the capabilities of the image analysis system and the time required to adapt and establish working procedures, efforts for the remainder of FY88 will be focused on collection and analysis of the following petrophysical parameters: grain and pore size distributions, porosity, and sorting.

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2. Ruzyla, K. Characterization of Pore Space by Quantitative Image Analysis. SPE Formation Evaluation, Aug. 1986, pp. 389-398.

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TABLE 1. - Porosity and air permeability of Cores From Naval Reserve field No. 3.

Core identification		Depth, ft	Porosity, %	Permeability, md
LA 54-36 5XFO	(A)	320.0	24.1	314
	(B)	320.0	22.3	289
FS 55-42 5X3F1	(A)	290.0	28.3	1151
	(B)	290.0	28.6	1051
FS 54-66 5X3FP	(A)	299.7	28.7	984
	(B)	299.7	29.1	1152
FS 54-66 5X3FP	(A)	301.0	28.4	1014
	(B)	301.0	28.3	888
FS 54-66 5X3FP	(A)	304.0	27.0	422
	(B)	304.0	26.5	462
FS 65-12 5X3Fa	(A)	293.8	25.9	522
	(B)	293.8	27.2	430
FS 65-36 5X3FP	(A)	276.0	30.0	1186
	(B)	276.0	28.0	774
FS 65-31 5X3FP	(A)	269.0	29.5	2077
	(B)	269.0	29.3	2019
FS 56-31 5X3FP	(A)	276.2	28.0	858
	(B)	276.2	28.2	852
FS 65-36 5X3FP	(A)	281.0	29.5	647
	(B)	281.0	27.9	585
FS 65-36 5X3FP	(A)	289.0	26.1	493
	(B)	289.0	26.3	529
LA 65-25	(A)	292.0	26.5	1044
	(B)	292.0	24.9	950

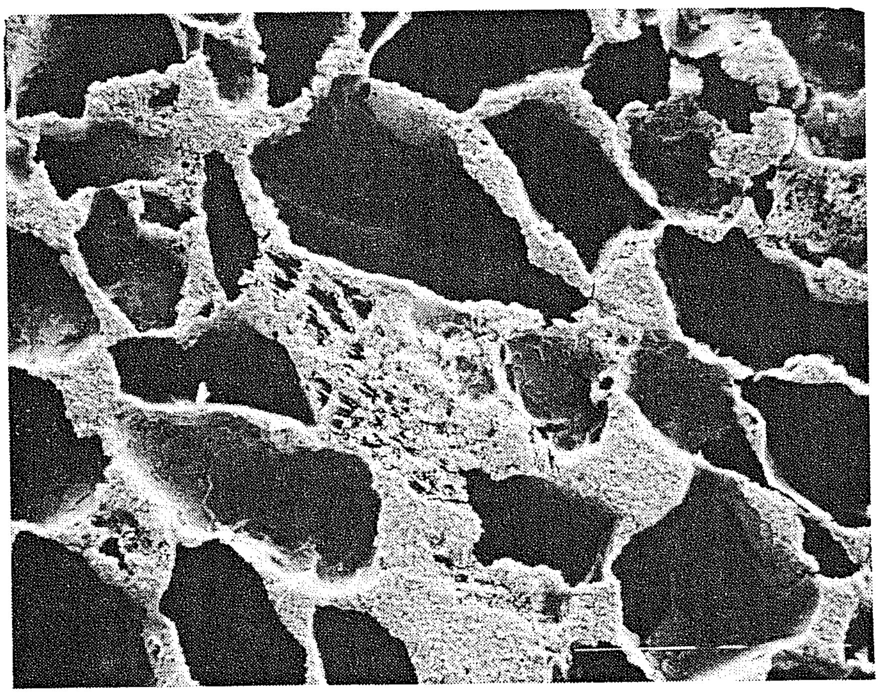

FIGURE 1. - SEM-BEI photograph of epoxy pore cast. This sample was taken from Bell Creek field, well 16, depth 4,328.5 ft, Powder River County, Montana. Width of image is 160 microns.

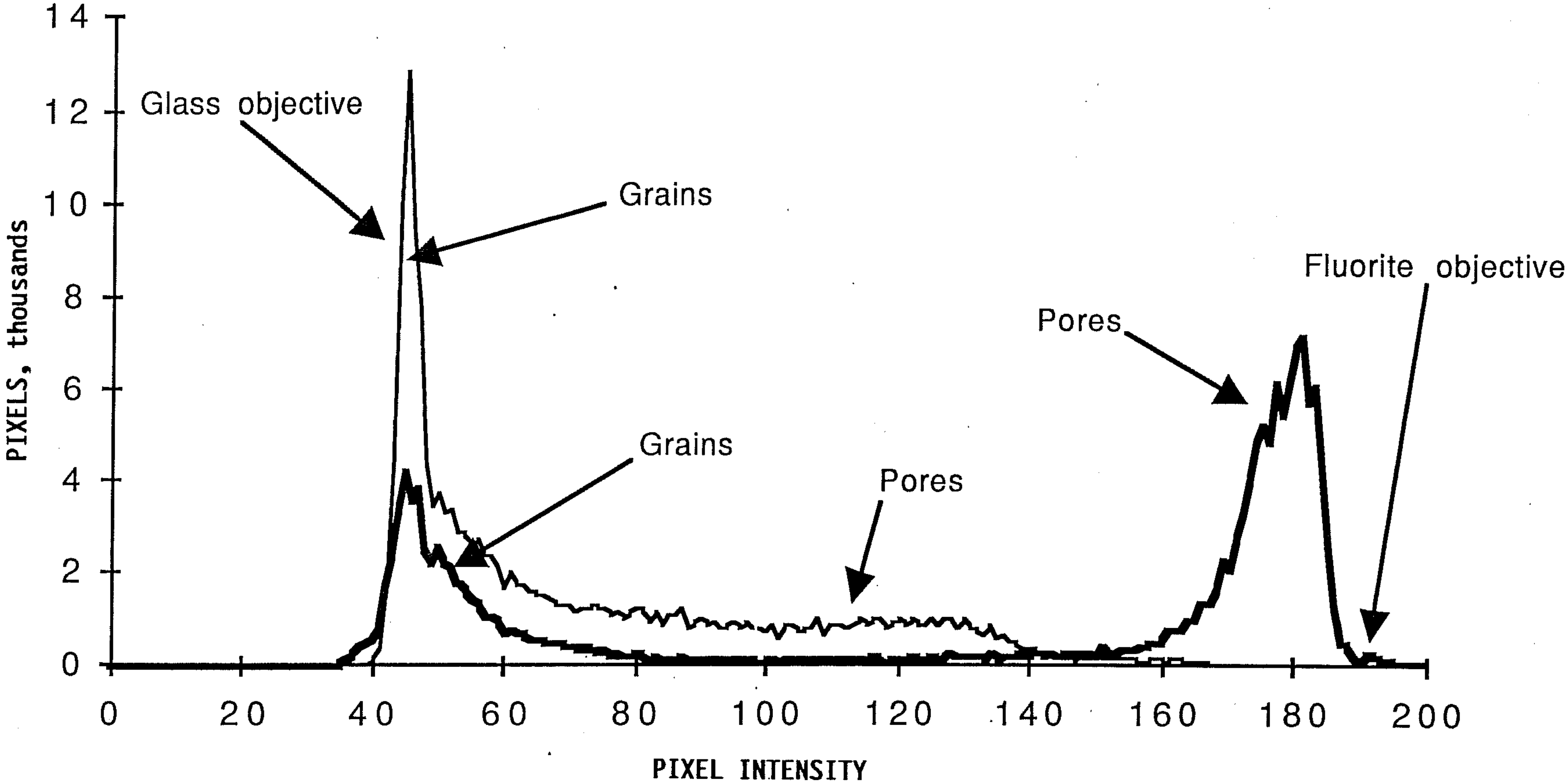

FIGURE 2. - Pixel intensity histogram showing contrast of images captured using glass and fluorite objectives. The fluorite objective has higher fluorescent intensity and better pore/grain contrast.

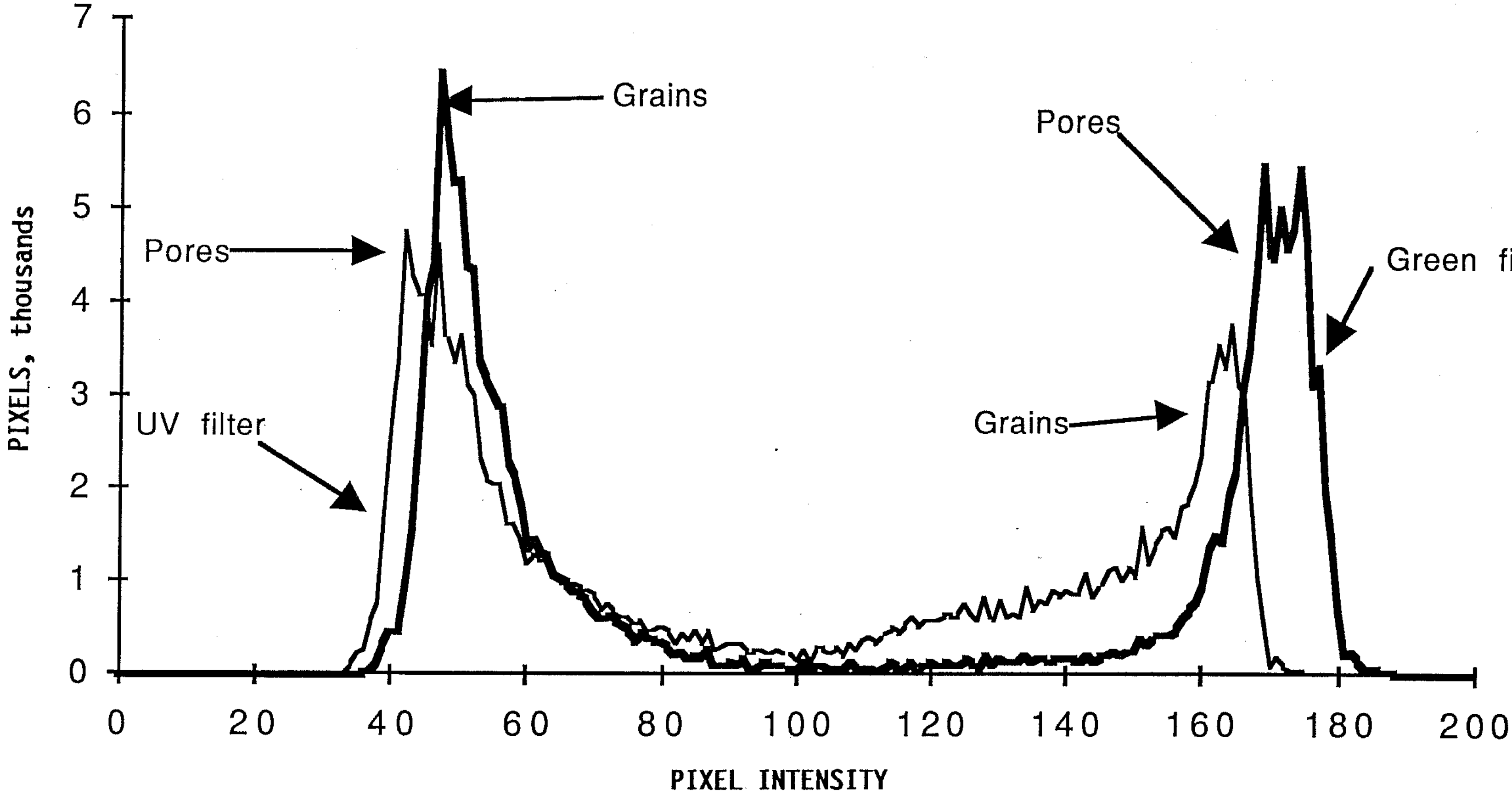

FIGURE 3. - Pixel intensity histogram showing fluorescent images captured using uv and green excitation filters. The green filter provides better pore/grain contrast.

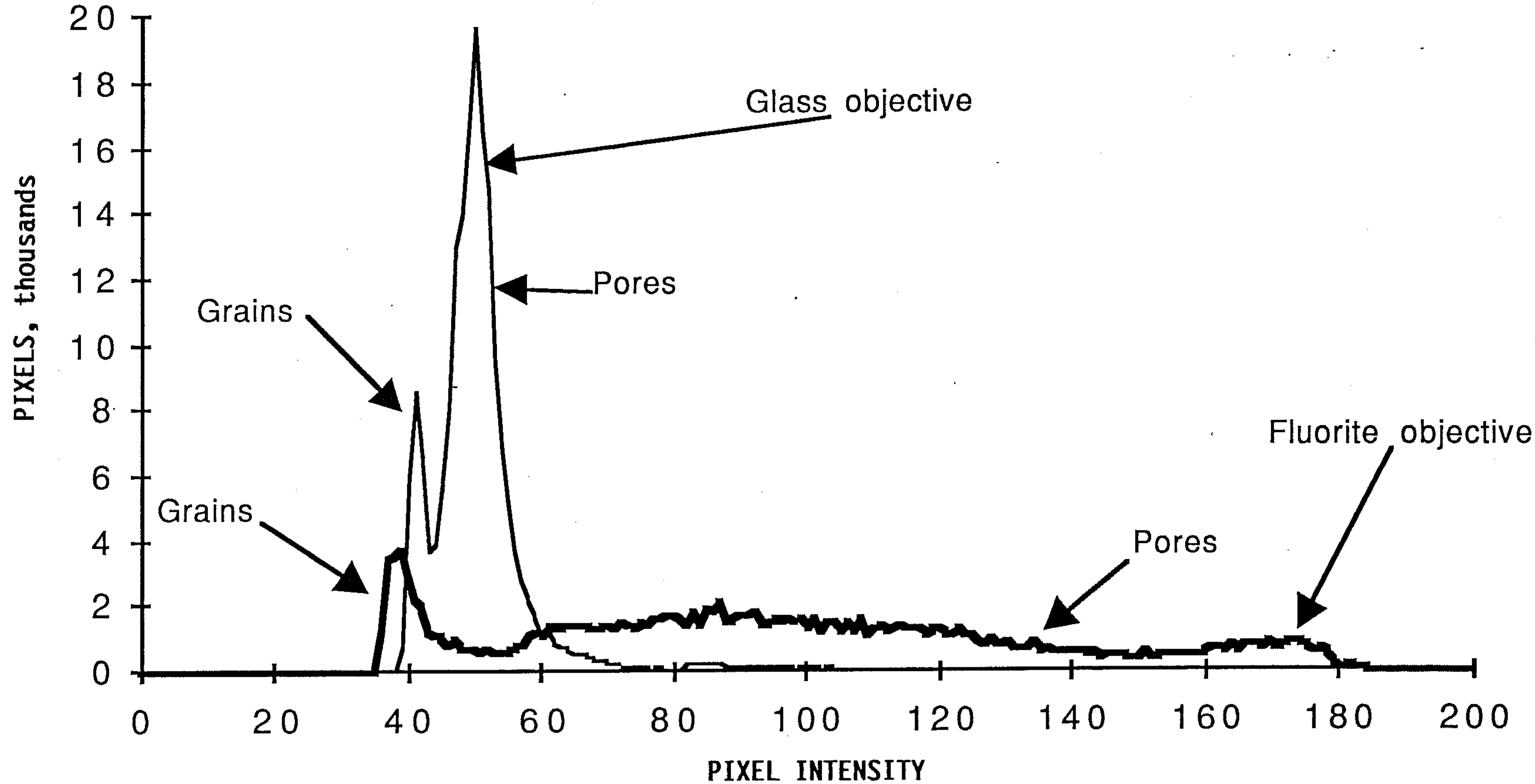

FIGURE 4. - Pixel intensity histogram of a thin section image containing large quantities of interstitual clays. With a glass objective there is virtually no contrast (intensity separation) between rock grains and pores. The pixel intensity is increased for pores using a fluorite objective, but the image lacks pore/grain contrast due to small grain/pore size.